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On the causal dynamics between economic growth, renewable energy consumption, CO_2 emissions and trade openness: Fresh evidence from BRICS countries

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ABSTRACT

The current study investigates the causal relationship between economic growth and renewable energy consumption in the BRICS countries over the period 1971–2010 within a multivariate framework. The ARDL bounds testing approach to cointegration and vector error correction model (VECM) are used to examine the long-run and causal relationships between economic growth, renewable energy consumption, trade openness and carbon dioxide emissions. Empirical evidence shows that, based on the ARDL estimates, there exist long-run equilibrium relationships among the competing variables. Regarding the VECM results, bi-directional Granger causality exists between economic growth and renewable energy consumption, suggesting the feedback hypothesis, which can explain the role of renewable energy in stimulating economic growth in BRICS countries.

Contents

1. Introduction

Energy is fundamental to sustain the development of nations. Particularly, fossil fuel energy has been the most component used worldwide. However, the expansion of energy-consuming activities in the developed and emerging countries, and waste in rich countries (especially the Gulf countries) lead to two major concerns: the depletion of the most easily accessible energy resources (mainly oil) and correspondingly, the problem of global warming caused by the rapidly increasing emissions of greenhouse gases such as carbon dioxide (CO_2) and methane. This global nature of energy challenges requires that renewable energy resources be appropriately managed and used. Renewable energy is commonly defined as energy generated from solar, wind, geothermal, tide and wave, wood, waste and biomass. Contrarily to conventional energy, renewable energy is clean, safe and

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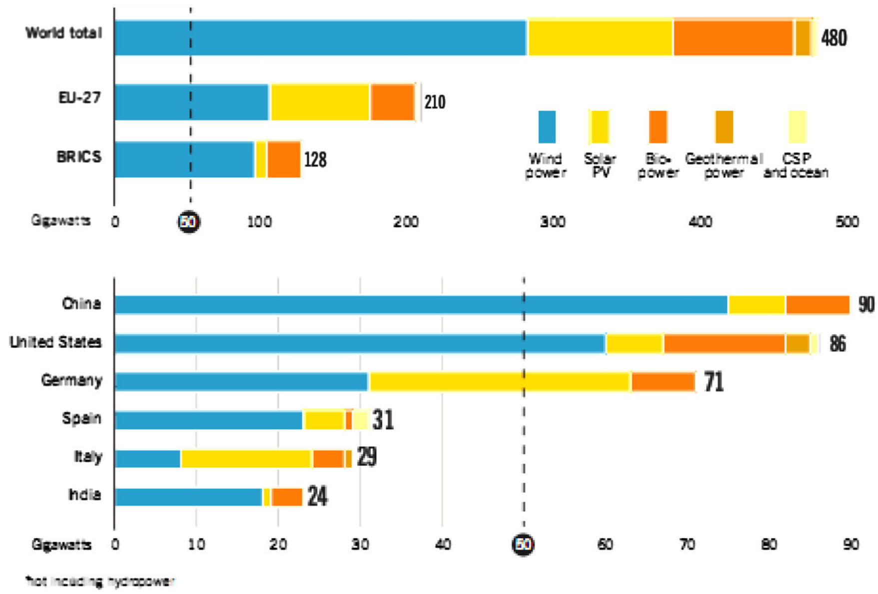

Fig. 1. Renewable power capacities in world, EU-27, BRICS, and top six Countries, 2012. .
Source: REN21 [1]

inexhaustible. Therefore, it is growing fast around the world and according to expectations it will edge out many conventional energy components and occupies a leading position in the overall share of energy consumption. For example, in China wind power generation increases more than generation from coal and passes nuclear power output [1].

Renewable energy quickly consolidates the role it plays in the energy supply around the world. That is, investment in renewables is picking up speed in many developing and emerging economies especially the BRICS countries.[1] According to REN21 [1], the BRICS accounted for 36% of total global renewable power capacity and 27% of non-hydro renewable capacity by the end of 2012. They occupy the second row behind the European Union, which accounts for 44% of the global total renewable power capacity (Fig. 1). In 2012, two BRICS nations (China and Brazil) were among the top five countries for renewable power capacity, while three BRICS nations (China, Brazil and India) were among the top six countries for non-hydro capacity.

On another side, as well documented, BRICS countries are growing very rapidly and have a sizeable impact on the global economy. For example, China and India had reached a real GDP growth of 8.9% and 6.2%, respectively over the period 1993–2003 [2]. This increase in economic growth has mutually been accompanied by an increase in energy demand. However, energy security emerges as a great concern due to substantial increases in prices of imported energy and because of limited reserves. Aside, the higher consumption of fossil fuels leads to higher greenhouse gas emissions, particularly CO_2, which contributes to global warming. According to IEA [3], three BRICS economies (China, Russia and India) were among the top five emitters of CO_2 in 2005. Such challenges require new thinking and new systems in the way to sustain energy. Developing enough the renewable energy sector is still among the promoting solution. That is, renewable energy sources may play a crucial role in expanding the domestic production and therefore they can be considered as an important determinant of economic growth.

[1] BRICS is a grouping acronym that refers to the countries of Brazil, Russia, India, China and South Africa.

It is undeniable that renewable energy sources play a crucial role in mitigating greenhouse gas emissions, particularly, the CO_2 which accounts for more than 60% of greenhouses gases [4]. According to IEA [4], renewable energy serves a vital role in the global 50% CO2 reduction target by 2050 if the long-term mean global temperature rise is to be limited to between 2 and 2.4 °C. While it is critical that countries like India and China have refused to make firm commitments to decrease their emissions of greenhouse gases, nonetheless, both countries have prioritised the development of renewable energies component to reduce carbon emissions. In addition to its success in combating global warming, the renewable energy tends to reduce the dependence on imported fossil-fuel energy and increase the supply of secure energy.

On the other hand, international trade can play a key role in the 'greening' of the energy sector, in particular, by facilitating the technology transfer for renewable energy and by responding to demand for sustainably energy sources. This demand has led to several trade opportunities, including exports of raw materials and components for renewable energy supply products and finished products, exports of energy from renewable sources, exports of renewable natural resources to produce energy [5]

Recently, the correlation between economic growth and renewable energy consumption has constituted a substantial field of research. Particularly, examining the significance of causality direction between the two variables is of great utility, since it may provide valuable insights for policy-makers. Based on the ARDL approach to cointegration and Granger causality, the current study aims to extend this line of research by investigating the renewable energy consumption–economic growth nexus in BRICS countries.

As shown in the subsequent section, when studying the renewable energy-economic growth nexus, most studies rely on a multivariate framework by including some control variables. This allows avoiding the omitted variables bias associated with the bivariate causality analysis. In fact, the BRICS countries face a dual challenge of promoting economic growth and mitigating the environmental impact of their growth techniques. That is, in the current study, CO_2 emissions and trade openness are used as control variables. Therefore, the results of this study are more robust, reliable and policy-orientated.

The plan of this paper is organised as follows: Section 2 provides a literature review on the causal relationship between economic growth and renewable energy consumption. Section 3 presents the data description, econometric methods and empirical results. Final section concludes the paper.

2. Literature review

Contrarily to the causal relationship between the non-renewable energy consumption and economic growth, which has generated a substantial body of literature since last decades, the economic growth-renewable energy use nexus can be considered as a recent field of research. Obviously, the data availability on the renewable energy is the most important factor that recently motivates the literature on the subject. That is, many papers have been appeared the last few years covering many geographic locations, using different econometric tools and including a range of control variables. Several studies have focused on a specific country while others have relied on a group of countries within a panel data framework.

Considering first the country-specific studies, Ocal and Aslan [6] examine the causal relationship between renewable energy use and economic growth in Turkey over the period 1990–2010. Using the ARDL approach and Toda–Yamamoto causality tests, the authors found that there exists a unidirectional causality running from economic growth to renewable energy consumption, supporting therefore the conservation hypothesis. Using the same causality tests, Menyah and Wolde-Rufael [7] test the hypothesis that nuclear energy consumption and renewable energy consumption reduce CO_2 emissions in the US during 1960–2007. Among others, they find that economic growth and CO_2 emissions Granger cause renewable energy consumption with no feedback. Yildirim et al. [8] apply the Toda–Yamamoto procedure and bootstrap-corrected causality test on the US data. Biomass energy consumption, hydropower energy consumption and biomass-wood-derived energy consumption are used along with the total renewable energy consumption, while employment and gross capital formation are used as control variables. Empirical evidence reports a unidirectional causality running from biomass energy consumption to economic growth while the neutrality hypothesis is supported between economic growth and all of the other renewable energy kinds as well as the total renewable energy consumption.

The case of Brazil was investigated by Pao and Fu [9] and Pao and Fu [10]. In the two studies, the authors examine the causal relationship between economic growth and aggregated and disaggregated renewable energy consumption. Pao and Fu [9] use annual data on GDP and four types of energy consumption, namely non-hydroelectric renewable energy consumption, total renewable energy consumption, non-renewable energy consumption and the total primary energy consumption, while Pao and Fu [10] consider, in addition to the above variables, total renewable energy consumption and hydroelectric, new renewables and nuclear energy consumption at disaggregated level. The two studies are based on a production function framework, controlling for real gross fixed capital formation and labour force. Mixed results are derived regarding the direction of causality between the variables. However, the authors insist on the role of renewable energy with its different components in promoting the Brazil's economic development.

Tugcu et al. [11] try to respond to the question of which type of energy (renewable or non-renewable) is more important for economic growth in G7 countries. They use the ARDL approach to cointegration and the recently Hatemi-J causality test [12] within a production function framework for each country over the period 1980–2009. In addition, physical capital, labour, research and development (R&D), and human capital are included as control variables. Empirical results show that based on the classical production function, bi-directional causality between renewable energy and economic growth is found for all countries. Nevertheless, this finding is not robust when augmenting the production function with human capital and R&D variables, since mixed results are found for each country. The study concludes that both renewable and non-renewable energy consumption have significant role in enhancing economic growth. Moreover, most of G7 countries should invest in R&D to benefit more from energy consumption.

Based on a bivariate model, Bildirici [13] focuses on biomass energy as a kind of renewable energy in ten Latin American developing countries. Using the ARDL approach to cointegration and Granger causality tests for each country, the author find that for most considered countries, there exists bi-directional causality between biomass energy and economic growth, while for others only biomass energy Granger causes economic growth. Therefore, this kind of energy may be considered as a solution for developing countries to meet their needs without expensive conversion devices.

From another strand, the panel data approach is also used in the context of renewable energy consumption–economic growth nexus, but with less extent than the time series analysis. For instance, Sadorsky [14] uses data for G7 countries over the period 1980–2005. The Pedroni approach to cointegration in panel data [15,16] and Granger causality tests are employed, while CO_2 emissions and oil price are used as control variables. Empirical evidence reveals that real income increases have positive and statistically significant effect on per capita renewable energy consumption, while oil price has a small and negative impact. Sadorsky [2], based on the same cointegration and causality techniques, investigates the causal relationship within a bivariate framework in eighteen emerging countries between 1994 and 2003. The empirical results confirm the conservation hypothesis in the long-run, while the neutrality hypothesis is supported in the short-run. Menegaki [17], by employing a random effect model to cointegration and a panel error correction model framework on a group of twenty seven European countries, does not confirm any Granger causality direction between renewable energy and economic growth, either in the short-run or long-run. That is, the neutrality hypothesis is supported and the author concludes that the lower levels of renewable energy consumption across Europe cannot play a significant role in promoting economic growth.

In a series of studies, Apergis and Payne [18–23] investigate the causal relationship between renewable energy consumption and economic growth for many groups of countries ranging from developed to developing countries. The authors use various cointegration techniques and causality approaches within a panel data framework. In the majority of cases, empirical results reveal that cointegration relationships and both short-run and long-run bi-directional causality exist among variables in question, proving the validity of the feedback hypothesis. Employing a panel error correction model within a multivariate model, Apergis et al. [24] examine the causal relationship between CO_2 emissions, nuclear energy consumption, renewable energy consumption and economic growth for a panel of nineteen developed and developing countries aver the period 1984–2007. Empirical evidence shows that there exists short-run bi-directional causality between renewable and nuclear energy consumption and economic growth, supporting therefore the feedback hypothesis. The long-run analysis reveals the existence of a unidirectional causality running from the consumption of both nuclear and renewable energy to economic growth, which suggests the validity of the growth hypothesis.

3. Empirical analysis

3.1. Data

The empirical analysis presented in this paper is based on annual time series of real gross domestic product (GDP), renewable energy

Table 1
Unit root tests.

Variable		ADF-MAX		Zivot–Andrews	
		Level	*First difference*	*Level*	*First difference*
Brazil					
GDP		0.349 (0)	−2.276 (1)*	−3.688 [2003] (2)	−5.713 [1981] (0)***
REC		−0.675 (0)	−2.984 (1)**	−2.636 [1990] (0)	−6.291 [1988] (0)***
CO_2		−1.168 (0)	−2.626 (1)**	−4.265 [1981] (1)	−4.732 [1980] (0)*
OPEN		−2.231 (0)	−4.651 (1)***	−3.776 [2001] (0)	−5.764 [1997] (0)***
Russia					
GDP		1.384 (0)	−0.774 (1)	−4.063 [2007] (1)	−3.706 [1999] (0)
REC		0.158 (1)	−1.754 (1)	−5.885 [1999] (0) ***	−7.637 [1999] (0)***
CO_2		1.196 (0)	−1.681 (1)	−3.806 [1998] (0)	−3.247 [1999] (0)
OPEN		0.186 (0)	−0.775 (1)	−6.474 [1999] (1) ***	−6.922 [1997] (1)***
India					
GDP		−0.291 (0)	−3.179 (1) **	−1.858 [2003] (4)	−5.367 [1991] (3) ***
REC		2.013 (0)	−3.214 (0) ***	−3.527 [2003] (2)	−5.217 [1980] (0)**
CO_2		−2.026 (1)	−4.093 (1) $^{*\ **}$	−4.046 [2001] (0)	−6.736 [1990] (0) ***
OPEN		−0.916 (0)	−7.379 (0) ***	−3.714 [1996] (2)	−3.758 [1981] (4)
China					
GDP		0.701 (0)	−2.411 (1) *	−3.101 [2002] (1)	−5.120 [1982] (4) **
REC		0.615 (0)	0.104 (1)	−1.375 [2004] (2)	−0.575 [2004] (4)
CO_2		−0.694 (0)	−3.336 (1) ***	−5.035 [1998] (1)	−7.644 [2003] (4) ***
OPEN		−2.248 (0)	−4.167 (1) ***	−4.615 [2004] (1)	−5.683 [2002] (4) ***
South Africa					
GDP		−0.127 (0)	−3.469 (1) ***	−3.312 [2002] (1)	−5.333 [1982] (0) **
REC		−1.280 (1)	−4.263 (1) ***	−4.073 [1987] (0)	−6.360 [1990] (0) ***
CO_2		−1.246 (1)	−3.982 (1) ***	−3.147 [1981] (0)	−7.056 [2003] (0) ***
OPEN		−2.213 (1)	−3.988 (1) ***	−3.714 [1989] (0)	−6.362 [1995] (2) ***
Critical values	1%	−3.981 (0)	−3.070 (0)	−5.570	−5.340
		−4.033 (1)	−3.187 (1)		
	5%	−3.261 (0)	−2.343 (0)	−5.080	−4.930
		−3.330(1)	−2.413(1)		
	10%	−2.844 (0)	−2.070 (0)	−4.820	−4.580
		−2.854 (1)	−2.084 (1)		

Note: For the ADF-MAX unit root test, critical values for variables in level are simulated using 38 observations and 1000 replications while for variables in first difference, critical values are simulated using 37 observations and 1000 replications. For the Zivot–Andrews unit root test, values in brackets present the time break. For both tests, values in parentheses indicate the lag length. Finally, ***, ** and * illustrate the statistical significance at the 1%, 5% and 10% levels, respectively.

consumption (REC), dioxide emissions (CO_2) and trade openness (OPEN) for the BRICS countries stretching from 1971 to 2010.[2] All the variables are taken from the online World Development Indicators database of the World Bank. GDP is measured in constant 2005 US dollars; Renewable energy, approximated by the combustible renewables and waste, is measured in 1000 metric tons of oil equivalent; CO_2 in metric tons while trade openness is defined as the sum of imports and exports divided by the GDP. All the variables (except OPEN) are expressed in per capita terms and transformed into natural logarithmic form.

3.2. Methodology and results

The subsequent analysis will be based on a three stage procedure. First, the integration order of the variables will be checked using ADF-MAX and Zivot–Andrews unit root tests. Second the long-run equilibrium relationships among the variables will be investigated based on the ARDL approach to cointegration. Finally, the Granger causality tests will be employed to examine the causal relationship between economic growth, renewable energy consumption, CO2 emissions and trade openness in BRICS countries.

3.2.1. Integration analysis

A preliminary and necessary step before conducting cointegration and causality analysis is the pre-testing of integration order of variables in question. When using the ARDL approach to cointegration, the unit root tests are mainly used to avoid the inclusion of I(2) variables. In this study, two types of unit root tests are applied: without and with structural break. We used the ADF-MAX test developed by Leybourne [25]. This test is a powerful modification of the standard ADF unit root test. It is given by the maximum between the usual ADF statistic and the ADF statistic computed using reversed data. In addition to its power properties, this test may, in some circumstances, be more robust to structural breaks than the conventional ADF test [26].

In modern times, generally for long time series data, along with the conventional tests, unit root tests which consider at least one structural break over time should be used. The period covered in the current study is 1971–2010. Most likely the series may suffer from endogenous structural breaks since they consist of annual figures more than thirty years. Therefore, we employ the conventional Zivot–Andrews unit root test with structural break [27]. The results of testing for the integration order are presented in Table 1.

Accordingly, the common components of GDP, REC, CO_2 and OPEN variables all turn out to be I(1), except the GDP variable for Russia and REC variable for China which are nonstationary both in levels and first differences under both the ADF-MAX and Zivot–Andrews unit root tests. Therefore, we must drop Russia and China

[2] Except Russia for which the data cover the period 1992–2010.

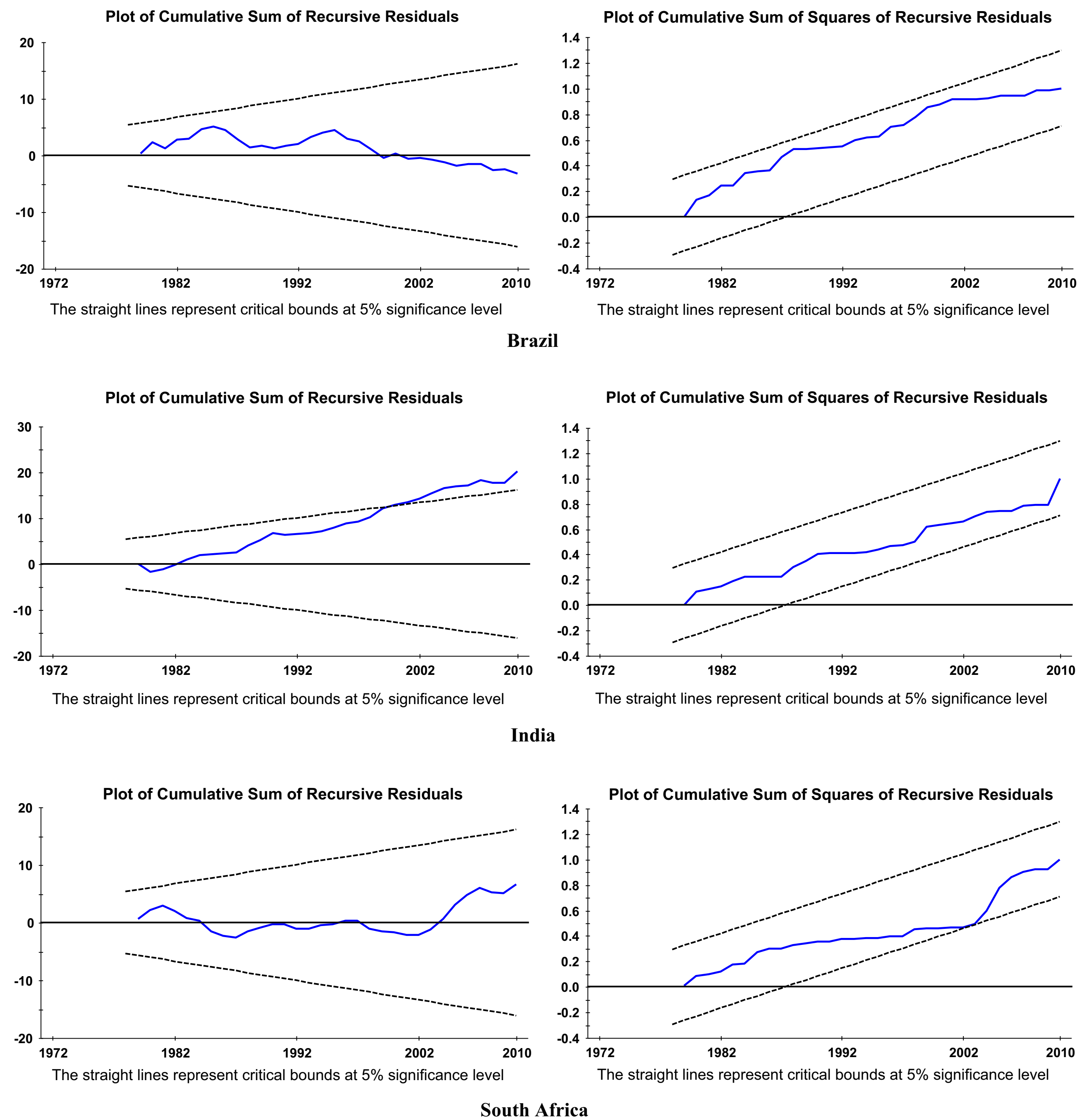

Fig. 2. Plots of CUSUM and CUSUMQ tests.

from the subsequent ARDL bounds testing approach to cointegration and causality analysis.

3.2.2. *Cointegration analysis*

The main purpose of this paper is to conduct a simultaneous analysis of the short- and long-run dynamics between economic growth and renewable energy consumption in the BRICS countries. Therefore, we employ the autoregressive distributed lag (ARDL) model, a relatively new technique to cointegration developed by Pesaran et al. [28]. This approach has been extensively used in empirical modelling due to its desirable properties compared to the standard Johansen cointegration technique developed by Johansen and Juselius [29]. First, it can be applied for smaller sample size and performs better than the Johansen's technique [30]. Second, The ARDL approach can accommodate stationary I(0), non-stationary I(1) or mutually cointegrated variables in the same regression, a task that is not possible with the Johansen's technique which requires that all the variables should be integrated of order one. Third, the ARDL approach deals with the endogeneity issues of some variables in the regression by providing unbiased long-run estimates with valid *t*-statistics [31,32]. Fourth, the ARDL approach allows assessing simultaneously both the short- and long-run effect of a particular variable on the other and it also separates short-run and long-run effects [33].

After testing for the unit roots, the subsequent step consists in investigating the long-run relationships between the variables

using the ARDL bounds testing approach. The ARDL representation between the competing variables may follows as:

$$\Delta GDP_t = a_{10} + \sum_{i=1}^{k1} \alpha_{1i}\Delta GDP_{t-i} + \sum_{i=0}^{l1} \beta_{1i}\Delta REC_{t-i} + \sum_{i=0}^{m1} \gamma_{1i}\Delta CO_{2t-1} + \sum_{i=0}^{n1} \lambda_{1i}\Delta OPEN_{t-i} + \phi_{11}GDP_{t-1} + \phi_{12}REC_{t-1} + \phi_{13}CO_{2t-1} + \phi_{14}OPEN_{t-1} + \varepsilon_{1t} \quad (1)$$

$$\Delta REC_t = a_{20} + \sum_{i=0}^{k2} \alpha_{2i}\Delta GDP_{t-i} + \sum_{i=1}^{l2} \beta_{2i}\Delta REC_{t-i} + \sum_{i=0}^{m2} \gamma_{2i}\Delta CO_{2t-1} + \sum_{i=0}^{n2} \lambda_{2i}\Delta OPEN_{t-i} + \phi_{21}GDP_{t-1} + \phi_{22}REC_{t-1} + \phi_{23}CO_{2t-1} + \phi_{24}OPEN_{t-1} + \varepsilon_{2t} \quad (2)$$

$$\Delta CO_{2t} = a_{30} + \sum_{i=0}^{k3} \alpha_{3i}\Delta GDP_{t-i} + \sum_{i=0}^{l3} \beta_{3i}\Delta REC_{t-i} + \sum_{i=1}^{m3} \gamma_{3i}\Delta CO_{2t-1} + \sum_{i=0}^{n3} \lambda_{3i}\Delta OPEN_{t-i} + \phi_{31}GDP_{t-1} + \phi_{32}REC_{t-1} + \phi_{33}CO_{2t-1} + \phi_{34}OPEN_{t-1} + \varepsilon_{3t} \quad (3)$$

$$\Delta OPEN_t = a_{40} + \sum_{i=0}^{k4} \alpha_{4i}\Delta GDP_{t-i} + \sum_{i=0}^{l4} \beta_{4i}\Delta REC_{t-i} + \sum_{i=0}^{m4} \gamma_{4i}\Delta CO_{2t-1} + \sum_{i=1}^{n4} \lambda_{4i}\Delta OPEN_{t-i} + \phi_{41}GDP_{t-1} + \phi_{42}REC_{t-1} + \phi_{43}CO_{2t-1} + \phi_{44}OPEN_{t-1} + \varepsilon_{4t} \quad (4)$$

where, Δ is the first difference operator; $a_{j0}, \alpha_j, \beta_j, \gamma_j, \lambda_j$, $\phi_{jj}(j = 1, \ldots, 4)$ are parameters to be estimated; kj, lj, mj, nj $(j = 1, \ldots, 4)$ are the optimal lag length to be used, and $\varepsilon_{jt}(j = 1, \ldots, 4)$ are white noise error terms.

From Eqs. (1)–(4), the existence of cointegration relationships between the variables is investigated based on the *F*-test resulting from restricting the coefficients of the lag level variables to zero. Pesaran et al. [28] provide critical value bounds for the *F*-test, which are interpreted as follows: if the *F*-statistics lie below the respective lower critical values, the null hypothesis of no cointegration cannot be rejected. Alternatively, if the *F*-statistics exceed their associated upper critical values, the null is rejected in favour of the alternative hypothesis, indicating cointegration. Finally, if the *F*-statistics fall within the two bounds, no conclusion could be made. Recently, in order to account for small sample sizes (from 30 to 80 observations), Narayan [31] calculates new critical values of the *F*-test. These latter are commonly used in studies conducted on limited data.

Before estimating the ARDL models, an important issue related to the potential instability of the estimated coefficients has to be investigated. Therefore, we implement in Fig. 2 the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMQ) stability tests based on the recursive regression residuals.

According to the Fig. 2, there are no instability issues in both Brazil and South Africa. However, for India, the CUSUM test indicates that there is a structural break in the GDP at the beginning of the 21st century. These results confirm those found above by using the Zivot-Andrews unit root test, which suggests that a structural break occurred in 2003. Therefore, following Ozturk and Acaravci [34], we include a dummy variable in the ARDL model for India and we conduct again the corresponding CUSUM and CUSUMQ tests (Fig. 3). Obviously, the new plots of the CUSUM and CUSUMQ statistics fall within the critical bounds at 5% significance level, indicating that the model has stable parameters over the time.

The bounds test results are shown in Table 2. It is worth noting that the Schwarz Bayesian Criterion (SBC) was used to select the optimal lag order of the ARDL models. Obviously, the bounds testing approach reveals mitigated results.

First, in most cases, the *F*-statistics lies above, at least, the 10% upper bound in the three BRICS countries confirming the presence of long-run equilibrium relationships. Second, when CO2 is assigned as dependent variable, the corresponding *F*-statistics are below the lower critical values, suggesting no cointegration. Finally, when the GDP (REC) is set as dependent variable in the case of South Africa (Brazil), the corresponding *F*-statistic falls within the bounds, emanating therefore to inconclusive results. The estimated ARDL models have passed a series of diagnostic tests of normality, heteroscedasticity, misspecification and serial correlation of the estimated residuals (Table 3).

Once the bounds testing approach confirms the existence of cointegration for most models, the long- and short-run coefficients may be estimated. Table 4 shows the empirical results of the long-

Table 2
Estimated ARDL models and bounds *F*-test for cointegration.

Model		Brazil		India[a]		South Africa	
F_{GDP} (GDP∣REC,CO_2,OPEN)		7.688***		5.462***		3.282	
F_{REC} (REC∣GDP,CO_2,OPEN)		3.046		13.859***		3.578*	
F_{CO_2}(CO_2∣GDP,REC,OPEN)		2.660		0.875		2.283	
F_{OPEN} (OPEN∣GDP,REC,CO_2)		6.168***		5.797***		3.788*	
Critical values		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
	1%	4.310	5.544	3.967	5.455	4.310	5.544
	5%	3.100	4.088	2.893	4.000	3.100	4.088
	10%	2.592	3.454	2.427	3.395	2.592	3.454

[a] Given the results of CUSUM and CUSUMQ tests, a dummy variable corresponding to the year 2003 is used in the ARDL model for India.
*** denote the statistical significance at the 1% level,
* denote the statistical significance at the 10% level.

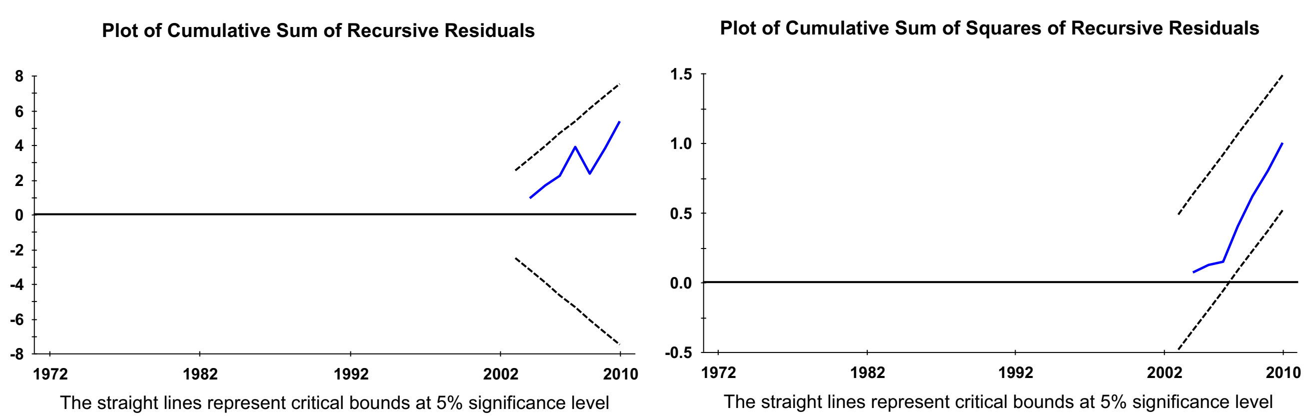

Fig. 3. Plots of CUSUM and CUSUMQ tests for India based on ARDL model with a dummy variable.

Table 3
Diagnostic tests.

	LM test (*p*-values)	ARCH test (*p*-values)	RESET test (*p*-values)	Normality test (*p*-values)
Brazil				
F_{GDP} (GDP|REC, CO_2,OPEN)	0.418	0.219	0.092	0.289
F_{REC} (REC|GDP, CO_2, OPEN)	0.518	0.187	0.357	0.264
F_{CO_2}(CO_2|GDP, REC, OPEN)	0.859	0.253	0.045	0.120
F_{OPEN}(OPEN|GDP, REC,CO_2)	0.347	0.162	0.299	0.219
India				
F_{GDP} (GDP|REC, CO_2,OPEN)	0.124	0.619	0.539	0.488
F_{REC} (REC|GDP, CO_2, OPEN)	0.764	0.235	0.655	0.318
F_{CO_2}(CO_2|GDP, REC, OPEN)	0.277	0.059	0.118	0.216
F_{OPEN}(OPEN|GDP, REC,CO_2)	0.427	0.701	0.427	0.397
South Africa				
F_{GDP} (GDP|REC, CO_2,OPEN)	0.405	0.269	0.734	0.573
F_{REC} (REC|GDP, CO_2, OPEN)	0.497	0.092	0.912	0.480
F_{CO_2}(CO_2|GDP, REC, OPEN)	0.421	0.128	0.712	0.213
F_{OPEN}(OPEN|GDP, REC,CO_2)	0.439	0.552	0.859	0.124

Note: LM test, ARCH test, RESET test and normality test refer to the Breusch-Godfrey Lagrange multiplier test for residual serial correlation, the autoregressive conditional heteroscedasticity test, the Ramsey's test for functional misspecification and the Jarque-Bera normality test., respectively.

run estimates using the ARDL modelling. For robustness check, the long-run coefficients are also estimated by fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) techniques. Generally, one can say that the coefficients remain consistent across the three estimation techniques. Accordingly, the estimated coefficients indicate that in the long-run, renewable energy consumption has a positive and significant effect on GDP in Brazil, validating therefore the energy-led growth hypothesis, while economic growth leads also to an increase in the renewable energy consumption. In the case of India and South Africa, either economic growth or renewable energy consumption shows its expected positive effect on each other, but this impact remains statistically insignificant. These findings prove the crucial role played by the renewable energy sector in Brazil compared to India and South Africa. On the other hand, CO_2 emissions and trade openness variables exhibit also their expected signs with regard to the literature. First, when the renewable energy consumption is set as dependent variable, coefficients associated with CO_2 emissions are mostly negative and statistically significant. This implies that an increase in CO_2 emissions reduces the renewable energy consumption in the three countries. This is because carbon emissions are mainly due to the use of fuel and other non-renewable energy, which lessens the promotion of renewable energy sources. Second, the CO_2 variable shows a positive and statistically significant coefficient in the growth models. The rise in carbon emissions, as a result of the development of main energy-intensive sectors (industry and transport), stimulates the economic growth. Third, in most cases, trade openness has positive and statistically significant effect on GDP, validating therefore the trade-led growth hypothesis widely discussed in the literature [35]. Based on the FMOLS and DOLS techniques, trade openness exerts also a positive effect on the renewable energy use in Brazil and India. This means that these two countries have benefitted from the technological transfer through international trade to promote the renewable energy sector.

Table 4
Long-run estimates.

	ARDL estimates		*FMOLS estimates*		*DOLS estimates*	
	Coef.	*p*-value	Coef.	*p*-value	Coef.	*p*-value
Brazil						
Dependant variable: GDP						
REC	0.554***	0.001	0.308**	0.033	0.363*	0.058
CO_2	0.652***	0.000	0.892***	0.000	0.909***	0.000
OPEN	0.660	0.300	−0.432	0.328	−0.809	0.271
Constant	8.561***	0.000	8.368***	0.000	8.503***	0.000
Dependant variable: REC						
GDP	2.046*	0.051	0.699**	0.030	1.219***	0.003
CO_2	−2.148**	0.041	−0.798***	0.009	−1.145***	0.001
OPEN	6.892	0.105	1.038*	0.089	0.740	0.432
Constant	−18.564**	0.037	−6.786***	0.009	−10.939***	0.001
Dependant variable: OPEN						
GDP	−0.406**	0.043	−0.106	0.272	−0.069	0.683
REC	0.027	0.798	0.069	0.246	0.007	0.946
CO_2	0.419**	0.014	0.238***	0.007	0.198	0.159
Constant	3.432**	0.038	1.052	0.194	0.692	0.634
India						
Dependant variable: GDP						
REC	−0.024	0.982	−0.578	0.180	−1.652***	0.000
CO_2	0.622**	0.017	0.385***	0.000	0.334***	0.000
OPEN	1.744***	0.000	1.656***	0.000	1.003***	0.000
*year*2003	0.111	0.461	0.050	0.385	0.234**	0.028
Constant	5.945***	0.009	4.734***	0.000	2.863***	0.001
Dependant variable: REC						
GDP	2.433	0.661	−0.071	0.404	−0.137*	0.097
CO_2	−2.063	0.620	−0.154***	0.001	−0.100**	0.017
OPEN	0.367	0.805	0.371**	0.014	0.401***	0.007
*year*2003	−0.280	0.638	−0.031	0.203	−0.005	0.906
Constant	−17.329	0.619	−1.557***	0.003	−1.154**	0.021
Dependant variable: OPEN						
GDP	0.852***	0.002	0.470***	0.000	0.464*	0.057
REC	−0.197	0.768	0.444*	0.068	1.001**	0.041
CO_2	−0.483*	0.073	−0.107	0.121	−0.027	0.888
*year*2003	−0.079	0.302	−0.013	0.695	0.038	0.702
Constant	−5.436**	0.041	−1.837***	0.008	−0.725	0.705
South Africa						
Dependant variable: GDP						
REC	0.494	0.338	−0.176	0.104	− 0.072	0.586
CO_2	0.452	0.418	0.269**	0.016	0.200	0.249
OPEN	1.914*	0.025	0.809***	0.000	0.863***	0.000
Constant	9.156***	0.000	7.270***	0.000	7.519***	0.000
Dependant variable: REC						
GDP	−0.125	0.820	−1.048***	0.008	−0.914	0.169
CO_2	−0.878***	0.001	0.911***	0.000	0.841***	0.001
OPEN	−0.513	0.372	0.596	0.114	0.232	0.741
Constant	−1.866	0.665	5.310*	0.078	4.506	0.376
Dependant variable: OPEN						
GDP	0.504*	0.070	0.784***	0.000	0.667**	0.012
REC	0.006	0.973	0.103	0.364	0.181	0.400
CO_2	−0.232	0.233	−0.246**	0.035	0.042	0.850
Constant	−3.258	0.125	−5.486***	0.000	−5.479***	0.007

*** denote the statistical significance at the 1% level,
** denote the statistical significance at the 5% and level,
* denote the statistical significance at the 10% level.

Table 5 presents the short-run estimates. Obviously, most conclusions derived from the long-run estimates remain robust in the short span of time. Importantly, the effect of renewable energy consumption on economic growth becomes more pronounced in South Africa, since the coefficient is positive and statistically significant at the 1% significance level. Similarly, the effect of economic growth on renewable energy consumption becomes statistically significant, at least, at the 95% confidence level in the three countries.

Table 5
Short-run estimates.

Model	Brazil Coef.	p-value	India Coef.	p-value	South Africa Coef.	p-value
Dependant variable: ΔGDP						
ΔREC	0.120***	0.004	−0.004	0.982	0.359***	0.009
ΔCO_2	0.473***	0.000	0.119**	0.048	−0.056	0.215
$\Delta OPEN$	0.143	0.220	0.334*	0.064	0.239***	0.000
$\Delta year2003$	–	–	0.021	0.454	–	–
ECT_{t-1}	−0.216***	0.001	−0.191*	0.058	−0.124*	0.078
Dependant variable: ΔREC						
ΔGDP	0.240**	0.033	0.056**	0.012	0.521***	0.009
ΔCO_2	0.099	0.427	−0.047***	0.000	0.135***	0.010
$\Delta OPEN$	0.811***	0.000	−0.082*	0.056	−0.079	0.340
$\Delta year2003$	–	–	−0.006	0.230	–	–
ECT_{t-1}	−0.117*	0.100	−0.023	0.632	−0.154***	0.001
Dependant variable: ΔOPEN						
ΔGDP	−0.147**	0.019	0.271***	0.002	1.170***	0.000
ΔREC	0.293***	0.001	−1.325*	0.056	0.002	0.973
ΔCO_2	0.009	0.890	−0.153***	0.003	−0.108	0.254
$\Delta year2003$	–	–	−0.025	0.240	–	–
ECT_{t-1}	−0.361***	0.001	−0.318**	0.044	−0.465***	0.002

*** denote the statistical significance at the 1% level,
** denote the statistical significance at the 5% level,
* denote the statistical significance at the 10% level.

Regarding the two control variables, CO_2 emissions and trade openness, empirical results are mixed when the renewable energy consumption is set as dependent variable and do not corroborate, therefore, the long-run results. However, in the growth model, the effects of these two variables are similar to those observed in the long-run.

The coefficients of the *ECTs* are negative and statistically significant corroborating, therefore, the established long-run equilibrium relationships between the competing variables. Particularly, when GDP is set as dependent variable, the *ECT* coefficient is −0.216, −0.191 and −0.124 in Brazil, India and South Africa, respectively. This implies that the speeds of convergence are of 21.6%, 19.1% and 12.4%, respectively. These coefficients indicate moderate speed of adjustment to shocks to the forcing variables (4.6 years in Brazil, 5.2 years in India and 8 years in South Africa).

3.2.3. Causality analysis

The existence of cointegration between series confirms that there ought to be at least, one causal relationship, but it fails to give its direction. Hence, we follow the famous procedure from Engle and Granger [36] to examine the short-run as well as the long-run causal dynamics between the competing variables. Following Engle and Granger [36], a vector error correction model (VECM) is used for testing the Granger causality among economic growth, renewable energy consumption, CO2 emissions and trade openness can be written as follows:[3]

$$\Delta GDP_t = b_{10} + \sum_{i=1}^{p1} \theta_{1i}\Delta GDP_{t-i} + \sum_{i=1}^{q1} \phi_{1i}\Delta REC_{t-i} + \sum_{i=1}^{r1} \delta_{1i}\Delta OPEN_{t-i} + \sum_{i=1}^{s1} \omega_{1i}\Delta CO_{2t-1} + \psi_1 ECT_{t-1} + \xi_{1t} \tag{5}$$

$$\Delta REC_t = b_{20} + \sum_{i=1}^{p2} \theta_{2i}\Delta GDP_{t-i} + \sum_{i=1}^{q2} \phi_{2i}\Delta REC_{t-i} + \sum_{i=1}^{r2} \delta_{2i}\Delta OPEN_{t-i} + \sum_{i=1}^{s2} \omega_{2i}\Delta CO_{2t-1} + \psi_2 ECT_{t-1} + \xi_{2t} \tag{6}$$

$$\Delta OPEN_t = b_{30} + \sum_{i=1}^{p3} \theta_{3i}\Delta GDP_{t-i} + \sum_{i=1}^{q3} \phi_{3i}\Delta REC_{t-i} + \sum_{i=1}^{r3} \delta_{3i}\Delta OPEN_{t-i} + \sum_{i=1}^{s3} \omega_{3i}\Delta CO_{2t-1} + \psi_3 ECT_{t-1} + \xi_{3t} \tag{7}$$

where, $b_{j0}, \theta_j, \phi_j, \delta_j, \omega_j (j=1,2,3)$ are parameters to be estimated; $\xi_{jt} (j=1,2,3)$ are white noise error terms; *ECT* is the error correction term derived from the corresponding long-run equilibrium relationship; The coefficients $\psi_j (j=1,2,3)$ of the *ECTs* represent the deviation of the dependent variables from the long-run equilibrium.

The error correction model allows testing for the existence of Granger causality in three possible ways [35]. First, the short-run Granger causality is investigated by testing the significance of the sum of lagged differences of explanatory variables by using the partial *F*-statistic. Second, the long-run causality is checked by examining the coefficients of the ECT_{t-1} based on *t*-statistics. Particularly, a long-run Granger causality exists if this coefficient is negative and statistically significant. Lastly, the strong Granger causality, which means that the two sources of causality are jointly significant, can be exposed by testing the joint hypothesis through the joint *F*-test on both ECT_{t-1} and sum of lagged differences of explanatory variables.

The Granger causality results are reported in Table 6. Empirical evidence shows that in the short-run, there exists bi-directional causal relationship between economic growth and renewable energy consumption (except for India) and between economic growth and trade openness (except for Brazil). This feedback relationship is also found between renewable energy consumption and trade openness in two BRICS countries (Brazil and India) while the neutrality hypothesis is supported in the case of South Africa. A unidirectional causality running from CO_2 emissions to both economic growth and trade openness is often derived from the results.

Regarding the long-run causality, all the *ECTs'* coefficients are negative and statistically significant suggesting bi-directional causal flows among the variables. However, an exception is registered for the renewable energy equation in the case of India, which is negative but not statistically significant. This suggests an absence of long-run causality running from economic growth, trade openness and CO_2 emissions to renewable energy consumption in this country. Finally, by using a joint *F*-test, empirical results suggest that a strong causality exists among variables for the three error correction models and three BRICS countries.

Comparing the findings of the current study to the literature, one can argue that they are consistent. The bi-directional causal relationship between renewable energy consumption and economic growth was previously found by Shahbaz et al. [37] in Pakistan, Tugcu et al. [11] in the case of G7 countries and Bildirici [13] in the case of six Latin American developing countries (Argentina, Bolivia, Costa Rica, Nicaragua, Panama and Peru). For instance, in the case of Brazil, Pao and Fao [9] find also bi-directional causality between economic growth and total renewable energy consumption. In the case of India, our conclusion that in the long-run the growth hypothesis is supported was previously established by Tiwari [38].

4. Concluding remarks

This paper employs the ARDL bounds testing technique and Granger causality to investigate the causal relationship between economic growth, renewable energy consumption, CO_2 emissions and trade openness in BRICS countries. Although a number of

[3] It should be noted that only equations where the null hypothesis of no cointegration is rejected will be estimated within the Granger causality framework. Hence, no error correction model will be estimated for the equation where CO_2 variable is set as dependent variable since no cointegrating relationship was found.

Table 6
VECM Granger causality analysis.

Dep. variable	Short-run F-statistics (p-value) ΔGDP	ΔREC	ΔOPEN	ΔCO_2	Long-run t-statistics (p-value) ECT_{t-1}	Joint (short- and long-run) F-statistics (p-value)
Brazil						
ΔGDP	–	9.517*** (0.004)	1.562 (0.220)	38.626*** (0.000)	−3.682*** (0.001)	24.633*** (0.000)
ΔREC	4.932** (0.033)	–	23.609*** (0.000)	0.644 (0.427)	−1.691* (0.100)	8.003*** (0.000)
ΔOPEN	6.095** (0.019)	13.468*** (0.001)	–	0.019 (0.890)	−3.560*** (0.001)	7.343*** (0.000)
India						
ΔGDP	–	0.0004 (0.982)	3.667* (0.064)	4.206** (0.048)	−1.960* (0.058)	4.538*** (0.003)
ΔREC	7.107** (0.012)	–	3.908* (0.056)	19.775*** (0.000)	−0.483 (0.632)	13.497*** (0.000)
ΔOPEN	11.458*** (0.002)	3.908* (0.056)	–	10.562*** (0.003)	−2.097** (0.044)	3.721*** (0.009)
South Africa						
Δ GDP	–	7.623*** (0.009)	18.809*** (0.000)	1.592 (0.215)	−1.817* (0.078)	9.818*** (0.000)
Δ REC	7.623*** (0.009)	–	0.937 (0.340)	7.420*** (0.010)	−3.757*** (0.001)	5.489*** (0.002)
Δ OPEN	17.505*** (0.000)	0.001 (0.973)	–	1.347 (0.254)	−3.382*** (0.002)	8.480*** (0.000)

*** denote the statistical significance at the 1% level,
** denote the statistical significance at the 5% level,
* denote the statistical significance at the 10% level.

studies have recently been conducted on the renewable energy consumption–economic growth nexus, there is no study that has investigated this relationship in BRICS countries as a whole. These countries have been recognised over the past years as key drivers of economic growth within the emerging markets and according to expectations they could become among the most dominant economies in the near future.

The empirical evidence from the ARDL approach indicates that renewable energy consumption has a positive effect on economic growth and vice versa. This effect is particularly more significant in Brazil compared to other countries. Regarding the Granger causality analysis, bi-directional causal flow exists between economic growth and renewable energy consumption, validating the feedback hypothesis. Obviously, these findings, while meaning that an increase in income is a core factor driving the development of the renewable energy sector, show the growing role of renewable energy in stimulating economic growth in BRICS countries. Empirical results show also the significant effect of trade openness and CO2 emissions in promoting the renewable energy consumption. On the one hand, trade openness enables BRICS countries to benefit more from 'green technologies' transfer that helps to invest more in the renewable energy sector. On the other hand, an increase in CO_2 emissions, which is the main cause of global warming, boosts policymakers to reduce this greenhouse gas by taking some measures of scaling down fossil energy consumption and relying more on energy from renewable sources.

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